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THREE-DIMENSIONAL PARTICLE-IN-CELL MODELING OF RELATIVISTIC ELECTRON BEAM PRODUCTION AND TRANSPORT FOR KRF LASER PUMPING*

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ABSTRACT The effects of diode geometry and externally applied magnetic fields on electron beam production and transport for KrF laser pumping has been studied using two and three dimensional particle-in-cell models. The efficiency with which electrons may be transported through the foil support structure depends critically on the size of the openings in the structure as well as the magnitude of the applied magnetic fields. As the electron diodes become larger the current which can be produced becomes limited by the self-magnetic field of the beam. Simulations show the diode current is limited to slightly more than the usual "critical current." However this electron flow is found to be unstable. The application of strong guide fields not only increases the current from the diode but tends to stabilize the electron beam.

INTRODUCTION

The design of efficient, high power Krypton-Fluoride (KrF) lasers for inertial fusion applications requires an accurate knowledge of the characteristics of the intense relativistic electron beams used to pump these lasers. The electron trajectories and resulting current densities for these beams depend critically on both the externally applied and self-consistent electric and magnetic fields in the diode.[1] Issues requiring large scale computation include the effects of diode geometry and applied external magnetic field on diode impedance and spatial uniformity of the electron beam. Because the vacuum in the diode must be separated by a foil from the high pressure laser gas, a substantial support structure known as a hibachi is used to support the foil. Another critical issue is the efficiency with which the beam may be transmitted through the hibachi.

The particle-in-cell model, ISIS, has been modified and used to study diode performance for existing laser pumping configurations and conceptual designs for higher power lasers.[2] This model follows the motion of charged particles in the electric and magnetic fields obtained from the full set of time-dependent Maxwell's equations in both two and three dimensions. Conducting and wave-transmitting boundary conditions may be applied to the field to model electrode and return current structures. Particle boundary conditions include space-charge limited emission from cathodes and particle absorption in conducting structures.

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HIBACHI TRANSMISSION EFFICIENCY

Figure 1 is a snapshot of the electron beam particles showing the geometry of the cathode and anode and transport through the hibachi structure from an ISIS simulation for the Intermediate Amplifier stage of the AURORA Laser at Los Alamos.[1] The hibachi is 118 in long and 21 in high and contains 168 openings, each 2 x 3.9 in^2. The cathode is seen to be slightly smaller, 113 x 18 in^2, and is located 3.15 in behind the hibachi. A foil, not shown modeled as a conducting plane is placed over the hibachi structure on the front side to contain the laser gas. Also not shown, but modeled, is the return current path. The simulation used 50 x 150 x 42 = 315 000 cells. Each opening in the hibachi contained 4 x 5 x 7 = 140 cells. Only a small fraction of the over 400 000 particles used are shown. A voltage rising to 800 kV was slowly applied to the diode and the calculation was run to steady state to obtain the snapshot. The diode produces a total current of about 340 kA.

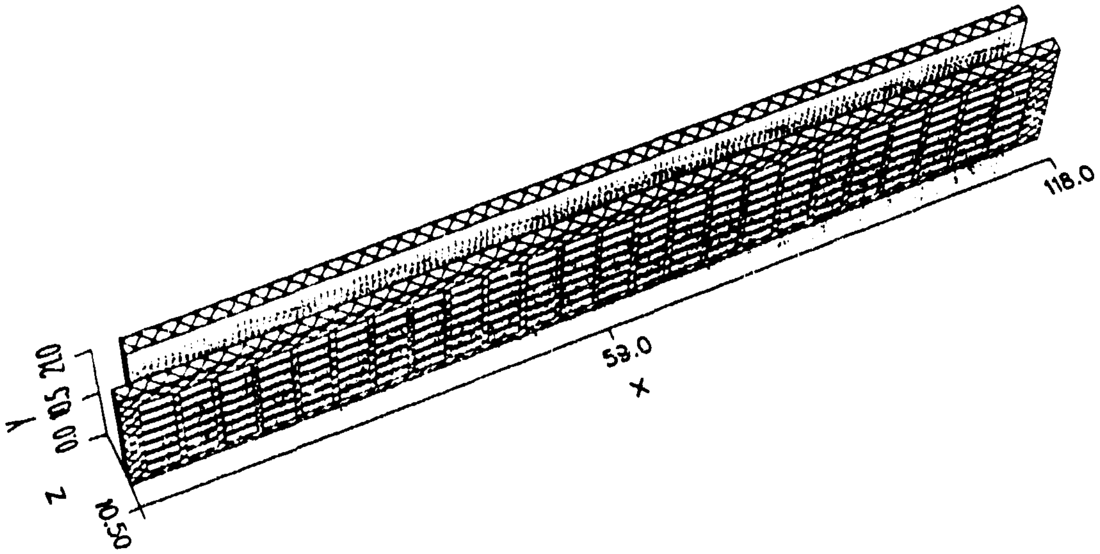

FIG. 1. Diode and hibachi structure for the AURORA Intermediate Amplifier taken from an ISIS particle-in-cell calculation.

The fraction of the electrons transported is less than the geometrical open area of the hibachi because the beam trajectories are skewed by the combination of external and self fields. Figure 2a shows the projection of the electrons on the x-y plane for all particles within 1 cm of the cathode. The emission is uniform and the particles are emitted from the cathode in a regular geometric pattern. Figure 2b shows the projection of the electrons on the x-y plane for all particles that have come through the hibachi and foil for the case of a 500 G magnetic field applied along the z-axis, in the direction of the electron beam. The effects of the beam rotation and skewing, as well as blockage by the hibachi is clearly seen. Computation of the electron trajectories and consequently the transmission efficiency is a complicated three-dimensional problem involving the self-consistent as well as applied fields.

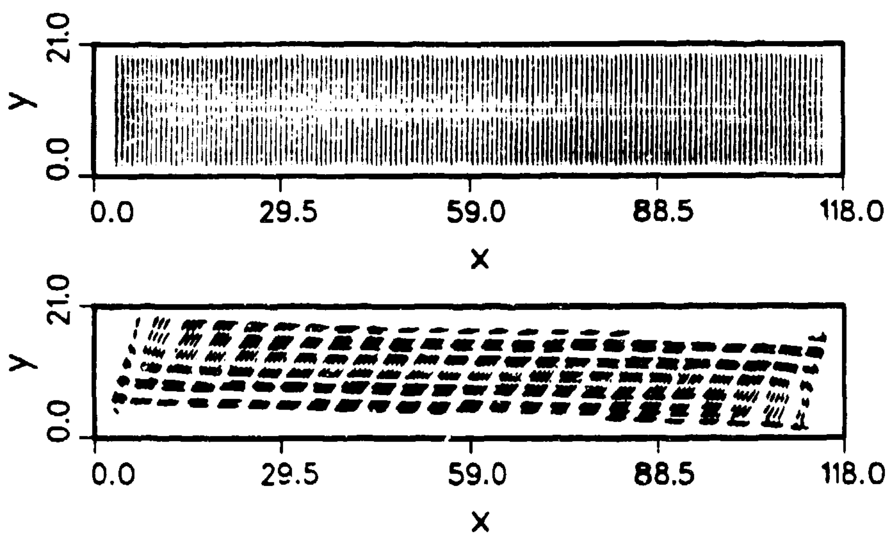

FIG. 2. (a) Projection of electron emitted from the cathode. (b) Electrons transmitted through the hibachi for 500 G applied field.

Other calculations show that for the hibachi opening size presently used, the transmission efficiency is a strong function of the applied magnetic fields. Recent developments show promise for significantly increased foil strength.[3] These foils would be able to span larger hibachi opening without rupturing from the high pressure laser gas. The results of 6 different calculations of the transmission efficiencies as a function of applied magnetic field, for the hibachi shown in Fig. 1 and for the case where the two vertical columns of openings were replaced by a single opening are summarized in Fig. 3. The hibachi geometrical open area of the hibachi increased from 65% to 80% for the larger openings. In addition, the sensitivity to applied magnetic field was greatly reduced. If such foils can be obtained, there are significant advantages for transmission efficiency in using larger hibachi openings.

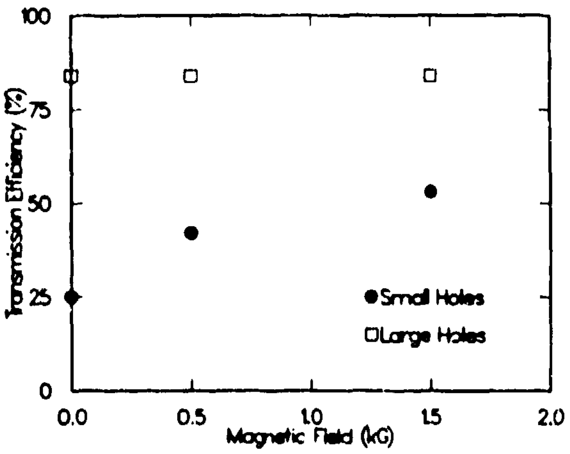

FIG. 3. Simulation results showing the effects of hibachi opening size and magnetic field on transmission efficiency.

CRITICAL CURRENT

For larger KrF amplifiers it may become necessary to segment the diodes used to pump the laser. An important issue for large area diodes is how large can the current be that can be produced in a single monolithic diode design. For cathodes whose transverse dimensions are large compared with the gap between the anode and cathode, the transverse electric field which is shorted at the conducting cathode and anode plane, will be small everywhere compared with the beam's own magnetic field. Thus the beam will experience a self-pinching. An electron on the outer edge of the beam will fail to reach the anode, when its gyroradius is equal to the anode-cathode (A-K) gap spacing, d. For a voltage on the diode which accelerates particles to an energy $(\gamma - 1)mc^2$, this condition is

$$\gamma\beta c/\omega_c = d, \tag{1}$$

where βc is the electron velocity and ω_c is the cyclotron frequency. For a cylindrically symmetric beam, the maximum self-field is given by $B = 2I/rc$, where r is the radius of the beam and I is the current. Using this expression we find the critical current is given, in cgs units, by

$$I_{crit} = \frac{mc^3}{2e}\gamma\beta\frac{r}{d} \tag{2}$$

For one-dimensional diodes an approximate expression for the electron current density for diodes with voltages greater than 0.5 MV has been obtained by Jory and Trivelpiece[4] (for lower voltages, the Child-Langmuir formula is accurate). If we approximate our cylindrically symmetric diode by multiplying this current density by the area of the cathode, i.e., πr^2, we obtain an expression for the current the diode should produce.

$$I = \frac{mc^3}{2e}(\gamma^{1/2} - 0.8471)^2(\frac{r}{d})^2. \tag{3}$$

Taking the ratio of Eq. (3) to Eq. (2) we find

$$\frac{I}{I_{crit}} = \frac{(\gamma^{1/2} - 0.8471)^2}{\gamma\beta}\frac{r}{d}. \tag{4}$$

A similar "one-dimensional" theory can be applied to long, thin cathodes such as the one depicted in Fig. 1. In this case, r in Eq. (4) is replaced by the narrow cathode width, w. Equation (4) predicts that for a fixed voltage, the diode current will exceed the critical current as the radius of the cathode, r, is increased relative to the A-K gap, d. For a diode voltage of 1 MV, this occurs for $r/d \approx 3.6$.

To test the validity of this model and to ascertain what happens to the diode when one exceeds the critical current, a series of 2-dimensional cylindrically symmetric simulations were performed with ISIS. The cathode consisted of a right circular cylinder with a radius 18 times the A-K gap. However, the radius over which the cathode was allowed to emit was varied to change the effective cathode radius, r. The diode voltage was 1 MV. No hibachi was modeled, only a conducting anode plane at which particles are absorbed.

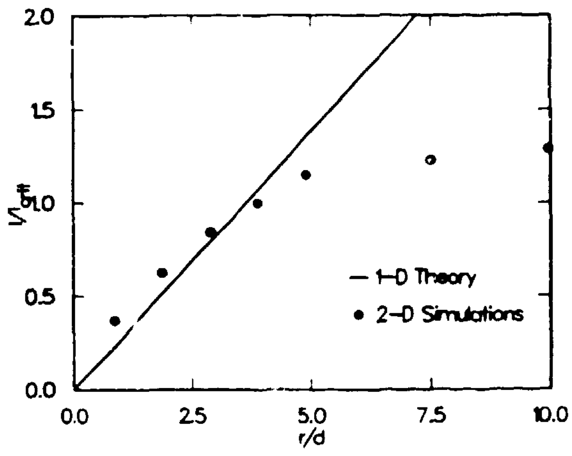

Fig. 4. Diode current as a function of cathode radius for idealized diode.

The results of 7 simulations are shown in Fig. 4 by the solid circles. The line is the one-dimensional theory of Eq. (4). When the cathode (emitting) radius, r, is below the critical value, the theory predicts the diode current fairly accurately. As r is increased beyond where the theory would predict the diode to exceed the critical current, the current deviates from the prediction of Eq. (3). For large r the diode current approaches 1.3 times the critical current. This does not mean that the diode current no longer increase as the cathode radius is made larger. It means that the current no longer scales as $(r/d)^2$ but as r/d.

Thus if a diode is pushed beyond the critical current, it does not fail to produce a beam, even without an applied magnetic field. However, the current scaling is not favorable with r. Furthermore, the outer edge of the beam strikes the anode at a sharp angle. Unless the hibachi has large openings, one would not expect to transmit a large fraction of the beam.

It is useful to express these concepts in terms of the diode impedance, $Z = V/I$, where $V = (\gamma - 1)mc^2/e$ is the diode voltage. Using either Eq. (3) or Eq. (2) and the condition from Eq. (4) for the current to be equal to the critical current, we find an expression for the critical impedance which is independent of the diode geometry:

$$Z_{crit} = 60\Omega \frac{(\gamma^{1/2} - 0.8471)^2}{\gamma + 1}. \quad (5)$$

For segmented designs with no applied magnetic field and no expanding flow so that the assumption of no transverse electric field is valid, one would like to keep the impedance of each diode above this value. For 1 MV ($\gamma = 3$), the critical impedance is 11.75Ω.

DIODE STABILITY

In addition to the large transverse motion observed for the electrons in simulations in which the diode current exceeds the predicted critical current, the electron current is observed to undergo rapid fluctuations in time. This effect is observed in both the 2-dimensional and 3-dimensional simulations. The diode current as a function of time, shown in Fig. 5, is taken from 2-dimensional simulation of the type discussed in the previous section for a cathode radius of 75 cm and an A-K gap of 10 cm. The diode voltage was 1 MV. The fluctuations begin near the time the diode voltage reaches its maximum. Initially the oscillations are small and a single frequency, which we have correlated with the beam plasma frequency. The amplitude of the fluctuations grow exponentially and the figure shows evidences of frequency doubling leading to chaotic oscillations.

The exact mechanism for the fluctations has not been determined. However, because diodes above the critical impedance did not exhibit the oscillations and those below Z_{crit} did, one may speculate that the mechanism is associated with the beam dynamics in the presence of its own magnetic field. As the current exceeds the critical current, the outer electrons do not reach the anode. The effect is to reduce the diode current and increase the space charge in the A-K gap, which also reduces the diode current. Once the current is reduced the outer electrons no longer experience as large a magnetic field. Therefore they will reach the anode creating a larger current and hence a larger magnetic field, starting the process over again. Simulations indicate that the oscillations may be stabilized if a strong magnetic field is applied. The calculations at no magnetic field for the Intermediate Amplifier exhibited current fluctations, while the ones at 1.5 kG were quiescent.

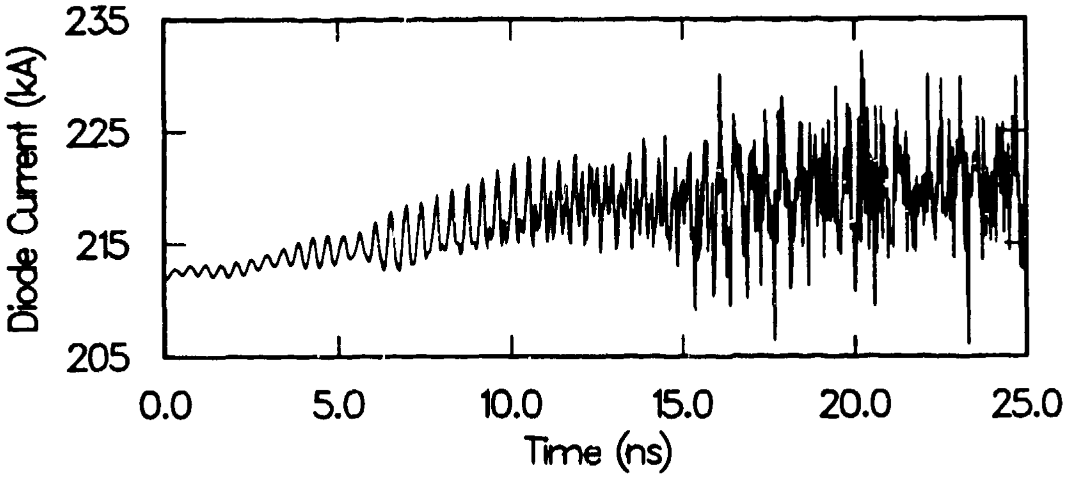

FIG. 5. Diode current as a function of time showing unstable behavior for diode impedances below the critical impedance Z_{crit} in Eq. (5).

REFERENCES

1. L. A. Rosocha and K. B. Riepe, Fusion Technol. 11, 576 (1987).
2. G. R. Gisler, M. E. Jones and C. M. Snell, Bull. Am. Phys. Soc. 29, 1196 (1984) and R. K. Cooper and M. E. Jones, in The Physics of Particle Accelerators, AIP Conference Proceedings 184, M. Month. and M. Dienes, eds., (1989) p. 1084.
3. R. Shurter, M. E. Jones, H. Oona, E. Rose, C. Sadler, V. A. Thomas, and J. Coogan, to appear in the Proceeding of the XIVth Inter. Sym. on Discharges and Electrical Insulation in Vac. Santa Fe, NM Sep. 1990.
4. H. R. Jory and A. W. Trivelpiece, J. Appl. Phys. 40, 3294 (1969).